Short Term Hydro-Thermal Scheduling using Artificial Immunue System

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ABSTRACT

Artificial Immune System is applied to determine the optimal hourly schedule of power generation in a hydrothermal system. A multi-reservoir cascaded hydroelectric system with a nonlinear relationship between water discharge rate, net head and power generation is considered. The water transport delay between connected reservoirs is taken into account. The transmission losses are also taken into consideration using loss coefficients. The developed algorithm is illustrated for a test system and the test results are compared with those obtained by using differential evolution and evolutionary programming technique. From numerical results, it is seen that artificial immune system based approach provides better solution.

Keywords:

Hydrothermal scheduling, cascaded reservoirs, artificial immune system

Nomenclature

a_{si}, b_{si}, c_{si}, d_{si}, e_{si}: cost curve coefficients of i th thermal unit

P_{sim} : output power of i th thermal unit at time m

$P_{si}^{\min}$, $P_{si}^{\max}$: lower and upper generation limits for i th thermal unit

P_{hjm} : output power of j th hydro unit at time m

$P_{hj}^{\min}$, $P_{hj}^{\max}$: lower and upper generation limits for j th hydro unit

P_{Dm} : load demand at time m

P_{Lm} : transmission loss at time m

Q_{hjm} : water discharge rate of j th reservoir at time m

$Q_{hj}^{\min}$, $Q_{hj}^{\max}$: minimum and maximum water discharge rate of j th reservoir

V_{hjm} : storage volume of j th reservoir at time m

$V_{hj}^{\min}$, $V_{hj}^{\max}$: minimum and maximum storage volume of j th reservoir

C_{1j}, C_{2j}, C_{3j}, C_{4j}, C_{5j}, C_{6j} : power generation coefficients of j th hydro unit

I_{hjm} : inflow rate of j th reservoir at time m

R_{uj}: number of upstream units directly above j th hydro plant

S_{hjm} : spillage of j th reservoir at time m

t_{lj} : water transport delay from reservoir l to j

N_h : number of hydro generating units

N_s : number of thermal generating units

m, M : time index and scheduling period

1. INTRODUCTION

Optimum scheduling of generation in a hydrothermal system is of great importance to electric utility systems. With the insignificant marginal cost of hydroelectric power, the problem of minimizing the operational cost of a hydrothermal system essentially reduces to that of minimizing the fuel cost for thermal plants under the various constraints on the hydraulic and power system network.

The main constraints include: the time coupling effect of the hydro sub problem, where the water flow in an earlier time interval affects the discharge capability at a later period of time, the cascaded nature of the hydraulic network, the varying hourly reservoir inflows, the physical limitations on the reservoir storage and turbine flow rate, the varying system load demand and the loading limits of both thermal and hydro plants.

The hydrothermal scheduling problem has been the subject of investigation for several decades. Most of the methods that have been used to solve the hydrothermal co-ordination problem make a number of simplifying assumptions in order to make the optimization problem more tractable. Some of these solution methods are mathematical decomposition [1], network flow [2], dynamic programming [3], deterministic optimization algorithm [4], lagrangian relaxation [5] and benders decomposition [6]. With the emergence of artificial and computational intelligence technology, attention has been gradually shifted to applications of such technology-based approaches to handle the complexity involved in real world problems. Stochastic search algorithms such as simulated annealing technique [7], evolutionary programming technique [8], genetic algorithm [9]-[10] and differential evolution [11] have been applied separately for optimal hydrothermal scheduling problem and circumvented the above mentioned weakness.

Artificial immune system (AIS) [12]-[18] has emerged in the 1990s as a new branch in computational intelligence. AIS is inspired by immunology, immune function and principles observed in nature. It is now interest of many researchers and has been successfully used in power system optimization problems [19]-[21].

This paper proposes AIS algorithm for short-term optimal scheduling of generation in a hydrothermal system which involves the allocation of generation among the multi-reservoir cascaded hydro plants and thermal plants with nonsmooth fuel cost function so as to minimize the fuel cost of thermal plants while satisfying the various constraints on the hydraulic and power system network. To validate the AIS-based hydrothermal scheduling algorithm, the developed algorithm has been illustrated for a test system [9]. The test results are also compared with those obtained by using of differential evolution (DE) and evolutionary programming (EP) technique. From numerical results, it is found that the proposed AIS based approach provides better solution.

2. PROBLEM FORMULATION

The hydrothermal scheduling problem is aimed to minimize the fuel cost of thermal plants, while making use of the availability of hydro power as much as possible. The objective function and associated constraints of the hydrothermal scheduling problem are formulated as follows.

2.1 Objective Function

The fuel cost function of each thermal generating unit considering valve-point effects is expressed as the sum of a quadratic and a sinusoidal function. The total fuel cost in terms of real power output can be expressed as

$$f=\sum_{m=1}^{\mathrm{M}}\sum_{i=1}^{\mathrm{N}_s}\left[a_{si}+b_{si}\mathrm{P}_{sim}+c_{si}\mathrm{P}_{sim}^{2}+\left|d_{si}\times\sin\left\{e_{si}\times\left(\mathrm{P}_{si}^{\min}-\mathrm{P}_{sim}\right)\right\}\right|\right] \tag{1}$$

$$\text{Affinity}=\frac{1}{f} \tag{2}$$

2.2 Constraints

(i) Power Balance Constraints:

The total active power generation must balance the predicted power demand and transmission loss, at each time interval over the scheduling horizon

$$\sum_{i=1}^{\mathrm{N}_s}\mathrm{P}_{sim}+\sum_{j=1}^{\mathrm{N}_h}\mathrm{P}_{hjm}-\mathrm{P}_{Dm}-\mathrm{P}_{Lm}=0 \quad m\in\mathrm{M} \tag{3}$$

The hydroelectric generation is a function of water discharge rate and reservoir water head, which in turn, is a function of storage.

$$\mathrm{P}_{hjm}=C_{1j}V_{hjm}^{2}+C_{2j}Q_{hjm}^{2}+C_{3j}V_{hjm}Q_{hjm}+C_{4j}V_{hjm}+C_{5j}Q_{hjm}+C_{6j} \quad j\in\mathrm{N}_h \;\; m\in\mathrm{M} \tag{4}$$

(ii) Generation Limits:

$$\mathrm{P}_{hj}^{\min}\le\mathrm{P}_{hjm}\le\mathrm{P}_{hj}^{\max} \quad j\in\mathrm{N}_h \;\; m\in\mathrm{M} \tag{5}$$

and

$$\mathrm{P}_{si}^{\min}\le\mathrm{P}_{sim}\le\mathrm{P}_{si}^{\max} \quad i\in\mathrm{N}_s,\; m\in\mathrm{M} \tag{6}$$

(iii) Hydraulic Network Constraints

The hydraulic operational constraints comprise the water balance equations for each hydro unit as well as the bounds on reservoir storage and release targets. These bounds are determined by the physical reservoir and plant limitations as well as the multipurpose requirements of the hydro system. These constraints include:

(a) Physical limitations on reservoir storage volumes and discharge rates,

$$V_{hj}^{\min}\le V_{hjm}\le V_{hj}^{\max} \quad j\in\mathrm{N}_h,\; m\in\mathrm{M} \tag{7}$$

$$Q_{hj}^{\min}\le Q_{hjm}\le Q_{hj}^{\max} \quad j\in\mathrm{N}_h,\; m\in\mathrm{M} \tag{8}$$

b) The continuity equation for the hydro reservoir network

$$V_{hj(m+1)}=V_{hjm}+\mathrm{I}_{hjm}-Q_{hjm}-S_{hjm}+\sum_{l=1}^{R_{uj}}\left(Q_{hl\left(m-t_{lj}\right)}+S_{hl\left(m-t_{lj}\right)}\right) \quad j\in\mathrm{N}_h,\; m\in\mathrm{M} \tag{9}$$

3. ARTIFICIAL IMMUNUE SYSTEM

The immune system of vertebrates including human is composed of cells, molecules and organs in the body which protect the body against infectious diseases caused by foreign pathogens such as viruses, bacteria, etc. To perform these functions, the immune system has to be able to distinguish between the body's own cells as the self cells and foreign pathogens as the non-self cells or antigens. After distinguishing between self and non-self cells, the immune system has to perform an immune response in order to eliminate non-self cell or antigen. Antigens are further categorized in order to activate the suitable defense mechanism and at the same time, the immune system also developed a memory to enable more efficient responses in case of further infection by the similar antigen.

Clonal selection theory explains how the immune system fights against an antigen. It establishes the idea that only those cells which recognize the antigen, are selected to proliferate. The selected cells are subjected to an affinity maturation process which improves their affinity to the selected antigens.

Clonal selection operates both on B-lymphocytes or B cells produced by the bone marrow and T-lymphocytes or T cells produced by the thymus. When the body is exposed to an antigen, B cells would respond to secrete specific antibodies to the particular antigen. Thereafter, a second signal from the T-helper cells, a subclass of T cells, would then stimulate the B cell to proliferate and mature into terminal (non-dividing) antibody secreting cells called plasma cells. In proliferation, clones are generated in order to achieve the state plasma cells as they are the most active secretors of the antibodies at a larger rate than rate of antibody secretion by the B cells. The proliferation rate is directly proportional to the affinity level i.e. higher the affinity level of B cells more clones is generated. Clones are mutated at a rate inversely proportional to the antigen affinity i.e. clones of higher affinity are subjected to less mutation compared to those which exhibit lower affinity. This process of selection and mutation of B cells is known as affinity maturation.

T cells do not secrete antibodies but play a central role in the regulation of the B cell response and are the most excellent in cell mediated immune responses. Lymphocytes, in addition to proliferating into plasma cells, can differentiate into long-lived B memory cells. These memory cells circulate through the blood, lymph and tissues, so that when exposed to a second antigenic stimulus, they commence to differentiate into large lymphocytes which are capable of producing high affinity antibody, preselected for the specific antigen that had stimulated the primary response.

Artificial immune system (AIS) mimics these biological principles of clone generation, proliferation and maturation. The main steps of AIS based on clonal selection principle are activation of antibodies, proliferation and differentiation on the encounter of cells with antigens, maturation by carrying out affinity maturation process, eliminating old antibodies to maintain the diversity of antibodies and to avoid premature convergence, selection of those antibodies whose affinities with the antigen are greater.

In order to emulate AIS in optimization, the antibodies and affinity are taken as the feasible solutions and the objective function respectively. Real number is used to represent the attributes of the antibodies.

Initially, a population of random solutions is generated which represent a pool of antibodies. These antibodies undergo proliferation and maturation. The proliferation of antibodies is realized by cloning each member of the initial pool depending on their affinity. In minimization problem, a pool member with lower objective value is considered to have higher affinity. The proliferation rate is directly proportional to the affinity of the antibodies. The maturation process is carried through hyper-mutation which is inversely proportional to the antigenic affinity of the antibodies. The next step is the application of the aging operator. This aging operator eliminates old antibodies in order to maintain the diversity of the population and to avoid the premature convergence. In this operator an antibody is allowed to remain in the population for at most τ_{B} generations. After this period, it is assumed that this antibody corresponds to local optima and must be eliminated from the current population, no matter what its affinity may be. During the cloning expansion, a clone inherits the age of its parent and is assigned an age equal to zero when it is successfully hyper-mutated i.e. when hyper-mutation improves its affinity.

4. DEVELOPMENT OF PROPOSED ALGORITHM

In this section, an algorithm based on artificial immune system for solving hydrothermal scheduling problem is described below.

Let $p_k = \left[\mathrm{P}_{s1}, \mathrm{P}_{s2}, \ldots, \mathrm{P}_{si}, \ldots, \mathrm{P}_{s\mathrm{N}_s}, Q_{h1}, Q_{h2}, \ldots, Q_{hj}, \ldots, Q_{h\mathrm{N}_h}\right]^{\mathrm{T}}$ be a trial matrix designating the k-th individual of a population to be evolved and $\mathrm{P}_{si} = \left[\mathrm{P}_{si1}, \mathrm{P}_{si2}, \ldots, \mathrm{P}_{sim}, \ldots, \mathrm{P}_{si\mathrm{M}}\right]$, $Q_{hj} = \left[Q_{hj1}, Q_{hj2}, \ldots, Q_{hjm}, \ldots, Q_{hj\mathrm{M}}\right]$. The elements P_{sim} and Q_{hjm} are the power output of the i th thermal unit and the discharge rate of the j th hydro plant at time m. The range of the elements P_{sim} and Q_{hjm} should satisfy the thermal generating capacity and the water discharge rate constraints in equations (6) and (8) respectively. Assuming the spillage in equation (9) to be zero for simplicity, the hydraulic continuity constraints are

$$V_{hj0} - V_{hj\mathrm{M}} = \sum_{m=1}^{\mathrm{M}} Q_{hjm} - \sum_{m=1}^{\mathrm{M}} \sum_{l=1}^{R_{uj}} Q_{hl\left(m-t_{lj}\right)} - \sum_{m=1}^{\mathrm{M}} \mathrm{I}_{hjm} \qquad j \in \mathrm{N}_h \tag{10}$$

To meet exactly the restrictions on the initial and final reservoir storage in equation (7), the water discharge rate of the j th hydro plant Q_{hjd} in the dependent interval d is then calculated by

$$Q_{hjd} = V_{hj0} - V_{hj\mathrm{M}} + \sum_{m=1}^{\mathrm{M}} \mathrm{I}_{hjm} + \sum_{m=1}^{\mathrm{M}} \sum_{l=1}^{R_{uj}} Q_{hl\left(m-t_{lj}\right)} - \sum_{\substack{m=1 \\ m \neq d}}^{\mathrm{M}} Q_{hjm} \qquad j \in \mathrm{N}_h \tag{11}$$

The dependent water discharge rate must satisfy the constraints in equation (8).

Also to meet exactly the power balance constraints in equation (3), the thermal generation $\mathrm{P}_{sd_g m}$ of the dependent thermal generating unit d_g can then be calculated using the following equation:

$$\mathrm{P}_{sd_g m} = \mathrm{P}_{Dm} + \mathrm{P}_{Lm} - \sum_{\substack{i=1 \\ i \neq d}}^{\mathrm{N}_s} \mathrm{P}_{sim} - \sum_{j=1}^{\mathrm{N}_h} \mathrm{P}_{hjm} \qquad m \in \mathrm{M} \tag{12}$$

The dependent thermal generation must satisfy the constraints in equation (6).

The cost function f is to be minimized. The algorithmic steps of AIS based on clonal selection principle are as follows:

Step1) Antibody of size N_P is randomly generated. These must be feasible candidate solutions that satisfy the practical operating constraints.

Step 2. The affinity value of each antibody in the population is evaluated using equation (2).

Step 3. The antibodies are cloned directly proportional to their affinities, giving rise to a temporary population of clones.

Step 4. The clones undergo maturation process through hyper-mutation mechanism whose rate is inversely proportional to their affinities. Each mutated clone must satisfy all the operating constraints.

Step 5. The affinities of the mutated clones are evaluated.

Step 6. Aging operator eliminates the antibodies and mutated clones which have more than τ_B generations from the current population.

Step 7. Tournament selection is done to select a new population of the same size as the initial population from the antibodies and mutated clones which are remained after application of aging operator.

Step 8. If the maximum number of generations is reached, output the optimal solution i.e. the highest affinity value obtained so far and terminates the proposed algorithm. Otherwise, go back to Step 3.

5. SIMULATION RESULTS

In this paper the performance of the proposed AIS-based hydrothermal scheduling problem is implemented using MATLAB 7 on a P-IV, 80 GB, 3.0 GHz personal computer. The proposed method has been applied to a test system which consists of a multi-chain cascade of four hydro units and three thermal units. The scheduling period is 24 hours with one hour time interval. The hydro sub-system configuration and network matrix including the water time delays are shown in figure 4, in the appendix. The load demand, hydro unit power generation coefficients, reservoir inflows, reservoir limits are given in tables 8, 9, 10 and 11 respectively in the appendix. The generation limits, cost coefficients of thermal units are given in table 12 in the appendix.

The problem is solved by using AIS algorithm. Here, the population size N_P and the maximum iteration number $\mathrm{N}_{\max}$ are taken as 50 and 400 respectively for the test system under consideration.

To validate the proposed AIS based approach, the same test system is solved using differential evolution (DE) and evolutionary programming (EP) technique.

In case of DE, the population size (N_P), scaling factor (F) and crossover constant (C_R) have been selected as 500, 0.35 and 1.0. The population size is taken 50 in case of EP. Maximum number of generations has been selected 400 for both DE and EP.

Table 1 shows the total cost obtained from AIS, DE and EP. The determined hydrothermal generation schedules and water discharge rates by using proposed AIS algorithm are shown in tables 2 and 3. The determined hydrothermal generation schedules and water discharge rates by using DE are given in tables 4 and 5. The determined hydrothermal generation schedules and water discharge rates by using EP are summarized in tables 6 and 7. Table 1 reveals that AIS has achieved lowest minimum cost. Figure 1 shows the cost convergence obtained from AIS, DE and EP.

Table 1: Comparison of cost

Method	Cost ($)
AIS	45433
DE	45969
EP	48062

Table 2: Hydrothermal generation (MW) schedule using AIS

Hour	P_{h1}	P_{h2}	P_{h3}	P_{h4}	P_{s1}	P_{s2}	P_{s3}
1	71.8234	65.7039	29.1734	217.5656	20.0000	211.6155	139.4310
2	92.5817	50.5402	54.1189	165.6318	157.8760	40.0471	231.5641
3	70.0014	53.9939	23.7185	122.1828	129.5166	256.7529	51.6207
4	78.0121	76.2547	46.2320	145.0842	48.1592	208.7785	51.0208
5	62.6004	66.4062	44.1705	132.1009	102.6624	127.6489	140.7897
6	67.8364	72.3945	46.7852	167.9228	102.0512	208.9843	141.4689
7	94.5086	55.0891	23.2943	173.2234	98.8136	124.7311	405.1276
8	80.0139	53.9194	43.7310	236.6677	172.4482	209.8057	229.1436
9	58.4335	70.3633	42.9410	251.7603	74.9751	209.1390	407.6690
10	56.3053	53.8907	50.6022	226.4792	20.0000	209.7554	497.5327
11	58.7106	56.2311	41.9201	248.4095	101.8293	210.5848	408.6869
12	74.1591	50.3339	38.4772	241.6708	69.7590	292.6938	409.6406
13	79.9996	85.4553	48.3107	196.2856	104.6774	214.1273	407.6147
14	104.4557	73.2047	48.2428	198.1783	103.1052	202.8754	317.8310
15	100.6341	52.8668	49.8672	254.9917	37.1926	208.5896	322.3367
16	80.7556	60.5444	50.9492	271.7901	173.2058	125.2788	318.0742
17	72.5990	69.3840	42.0679	252.1790	20.0000	209.1360	408.9391
18	79.7597	55.7259	56.0643	244.2095	174.5975	214.8082	316.8189
19	64.4397	62.6780	52.4424	224.2113	74.4668	209.8371	407.0209
20	64.4639	69.4904	56.4943	257.5805	94.2513	207.3418	317.9596
21	90.2071	47.8455	57.5221	268.1632	20.2087	40.5135	408.9404
22	87.9591	65.5452	43.1193	296.4617	104.2330	210.5357	58.7539
23	58.4318	46.6280	54.0516	290.9288	145.1913	126.1552	137.4614
24	57.4695	51.7444	55.4865	275.0541	100.7017	40.0000	229.6560

Table 3: Hourly plant discharge ($\times 10^4 m^3$) using AIS

Hour	Q_{h1}	Q_{h2}	Q_{h3}	Q_{h4}
1	7.4923	8.6492	23.1053	13.6956
2	11.3952	6.2747	15.1734	9.6111
3	7.2206	6.6299	29.2546	8.5292
4	8.4289	10.3139	15.3465	9.1301
5	6.2359	8.5376	29.8321	13.6244
6	6.9477	9.7434	13.0899	11.3238
7	12.4796	6.9984	21.4446	11.4096
8	9.1656	6.9133	16.0919	16.5749
9	5.8679	9.8137	16.6103	19.3368
10	5.4754	7.0770	13.1506	13.9435
11	5.6215	7.2544	18.2051	16.8570
12	7.4604	6.2069	18.7023	15.2781
13	8.2511	13.1254	14.8473	10.4395
14	14.1109	10.6643	15.2593	10.1064
15	12.6908	7.0503	14.7310	15.6278
16	8.4030	8.1036	14.5500	17.4989
17	7.1689	9.7900	19.6052	14.8417
18	8.1472	7.6097	14.9234	13.9514
19	6.1021	9.0471	17.2119	11.8128
20	6.0932	10.8484	14.8819	14.9923
21	9.8963	7.0540	14.7944	16.3219
22	9.5944	10.0802	20.2685	20.0000
23	5.4512	6.7675	16.6281	20.0000
24	5.3000	7.4469	16.5464	17.9098

Table 4: Hydrothermal generation (MW) schedule using DE

Hour	P_{h1}	P_{h2}	P_{h3}	P_{h4}	P_{s1}	P_{s2}	P_{s3}
1	83.0379	55.4723	39.0311	195.4127	34.4455	212.1036	135.8153
2	71.7950	60.5950	53.4523	196.4438	103.4007	125.5305	176.5915
3	73.4385	54.3909	45.3717	169.5428	98.8799	124.5580	139.8967
4	66.2004	57.6141	51.9554	143.4003	70.0888	125.9708	139.7943
5	78.0740	67.9949	40.8967	142.2433	102.0390	129.9381	114.2687
6	76.3542	63.3878	31.6673	174.1398	112.1377	209.8088	140.4493
7	85.2513	62.4363	19.8855	171.2562	105.6827	122.1912	408.6963
8	74.5192	62.1590	50.7593	185.9772	125.0211	209.4874	321.1959
9	80.2843	71.7400	40.3900	210.8814	98.2406	204.8375	409.9186
10	74.1990	66.8961	49.1727	214.3311	84.7707	207.2319	409.0574
11	77.3368	63.0308	49.4626	215.7939	101.8863	209.8324	409.0248
12	67.7222	72.4041	39.3091	223.2499	103.0011	277.4630	392.8722
13	83.2597	65.4846	49.1068	234.5224	112.6748	215.3335	372.9801
14	68.6633	60.5684	41.8581	244.0225	103.7971	209.8306	319.3603
15	82.7858	65.3513	54.3667	226.2738	68.9228	209.8116	319.2816
16	83.0294	71.7039	44.6563	225.0234	107.0947	125.3402	431.0707
17	70.3601	58.5546	53.5472	251.9481	99.5912	214.7761	319.2092
18	86.2238	59.5444	56.5876	252.4167	95.5011	195.6637	398.9988
19	79.0858	60.9799	57.5961	240.8584	103.2893	230.0075	316.3327
20	71.0778	74.9853	51.8889	241.8371	100.8847	208.9540	318.2537
21	63.1448	72.5782	54.8836	237.7377	94.8288	168.1070	229.5742
22	96.1838	58.9460	26.6757	265.1536	70.5463	209.6319	139.7170
23	79.5338	56.2234	52.7110	285.2911	102.4098	121.9618	159.5101
24	89.4889	67.9722	55.6455	286.4694	127.4616	40.6164	139.7675

Table 5: Hourly plant discharge ($\times 10^4 m^3$) using DE

Hour	Q_{h1}	Q_{h2}	Q_{h3}	Q_{h4}
1	9.3900	6.9497	21.2930	11.3572
2	7.4625	7.6591	15.8795	12.3978
3	7.6448	6.6613	18.1371	10.7714
4	6.6101	6.9412	14.5708	9.2545
5	8.3409	8.4337	19.1058	10.1961
6	8.1719	7.7006	21.0849	12.1472
7	9.8868	7.6118	22.8905	11.3632
8	8.0287	7.7196	11.1866	12.0963
9	8.9669	9.5187	19.0729	14.6682
10	7.8782	8.7747	16.1337	14.4444
11	8.2332	8.0673	16.0728	13.7218
12	6.6974	9.6979	19.4848	13.4565
13	8.9093	8.5795	16.4476	15.0548
14	6.6904	7.7925	19.2375	15.7018
15	8.5748	8.4857	12.3245	13.5412
16	8.5509	9.6270	19.1695	13.1287
17	6.7612	7.4541	15.7710	15.4584
18	8.9753	7.6602	12.1421	15.3920
19	7.9102	8.0769	14.4662	13.6510
20	6.8480	11.0746	17.9008	13.8923
21	5.8969	11.0149	16.6590	12.9495
22	10.8978	8.4443	23.4759	15.6595
23	8.0405	7.8971	16.9803	18.9149
24	9.6332	10.1578	15.6406	19.9528

Table 6: Hydrothermal generation (MW) schedule using EP

Hour	P_{h1}	P_{h2}	P_{h3}	P_{h4}	P_{s1}	P_{s2}	P_{s3}
1	70.6200	49.0000	25.2661	112.4993	64.0483	300.0000	136.3117
2	99.2400	78.4843	17.3385	162.6479	20.0000	279.5163	138.0382
3	51.9343	58.7328	44.5558	122.2628	35.5019	255.0682	137.5869
4	92.7332	61.0731	41.0616	146.6958	20.0000	151.3721	141.5977
5	57.4873	70.3141	48.8258	138.1723	20.0000	172.7254	168.0382
6	73.6780	56.3643	52.0205	198.8746	85.7609	213.5351	126.2108
7	51.3634	49.2054	27.2021	123.3311	175.0000	300.0000	242.8808
8	94.9082	49.1101	50.2445	285.5728	116.3144	148.5485	280.3858
9	87.0314	54.1682	32.0301	250.0230	89.0188	196.6445	406.9780
10	69.6887	50.4732	46.2513	254.0269	75.6162	196.8340	412.7615
11	92.4502	84.4329	38.2342	243.7077	94.7675	135.6962	439.3710
12	81.9139	60.9693	40.2823	244.0238	113.5187	300.0000	330.5752
13	97.1529	72.5216	43.4347	256.6609	175.0000	229.4387	253.7694
14	50.9347	49.8039	42.5304	254.2212	28.3491	300.0000	322.0618
15	69.7215	61.1332	49.2722	278.7546	79.6587	152.0408	337.5396
16	68.7395	63.0820	40.7655	284.8551	160.4270	193.1340	266.1165
17	53.8163	84.6136	39.0245	214.8058	155.2848	300.0000	218.3485
18	85.7858	87.5753	50.1568	288.5998	85.8601	214.8620	325.4958
19	54.1882	72.0905	51.9357	305.0704	20.0000	275.9258	306.8483
20	93.4133	51.7545	50.4758	250.5204	83.8795	300.0000	232.9285
21	59.1011	42.9711	52.3989	300.0169	85.7754	126.6209	255.0713
22	54.0044	44.7356	53.5506	297.3547	20.0000	94.5109	310.3078
23	56.3437	79.3386	55.6198	296.1181	20.0000	40.0000	317.6570
24	58.8113	65.6309	58.9075	272.2352	74.6100	40.0000	239.8174

Table7: Hourly plant discharge ($\times 10^4 m^3$) using EP

Hour	Q_{h1}	Q_{h2}	Q_{h3}	Q_{h4}
1	7.3148	6.0000	28.9895	6.4197
2	14.2478	11.0414	25.9467	9.3072
3	5.0000	7.5649	16.3017	6.0000
4	11.6837	7.8038	16.9207	8.3103
5	5.7111	9.3281	10.6053	8.3344
6	7.9694	7.0626	12.7754	11.9744
7	5.0000	6.0124	30.0000	6.6604
8	12.8892	6.0000	14.1618	20.0000
9	10.7988	6.6461	30.0000	20.0000
10	7.4820	6.0000	14.2549	17.1550
11	12.0973	11.9966	18.3254	16.3921
12	9.3921	7.5743	17.6771	14.5921
13	15.0000	9.5945	16.3931	16.1929
14	5.0000	6.0000	28.2554	20.0000
15	7.1686	7.4292	11.7586	18.0830
16	6.8970	7.5969	18.9886	18.9905
17	5.0000	11.9054	19.2118	11.0084
18	9.2829	13.9822	14.4977	18.8956
19	5.0000	10.9031	11.9679	20.0000
20	10.7954	7.4358	15.0330	13.9259
21	5.6043	6.0272	10.1091	19.7012
22	5.0000	6.0000	16.2196	19.3475
23	5.2170	12.3770	10.0000	20.0000
24	5.4484	9.7185	12.1456	17.5741

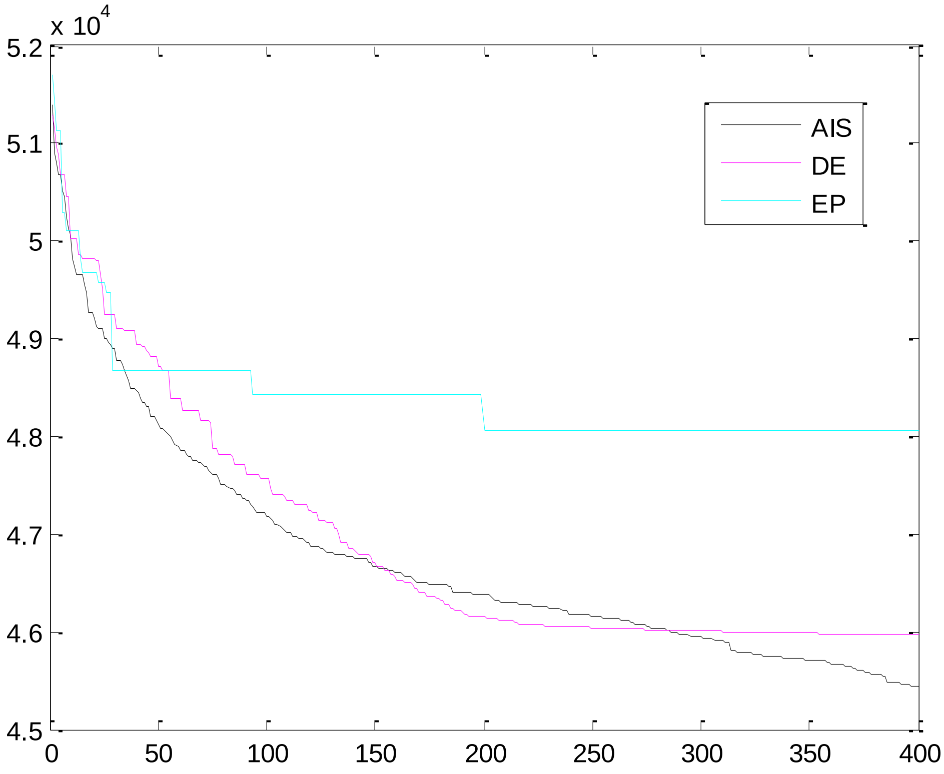

Fig. 1: Cost convergence

6. CONCLUSION

A novel approach based on artificial immune system has been presented to solve the short-term hydrothermal scheduling problem. Numerical results show that highly near-optimal solutions can be obtained by artificial immune system algorithm when compared with the differential evolution and evolutionary programming technique. The same problem can be solved using other optimization technique and can be compare with this technique

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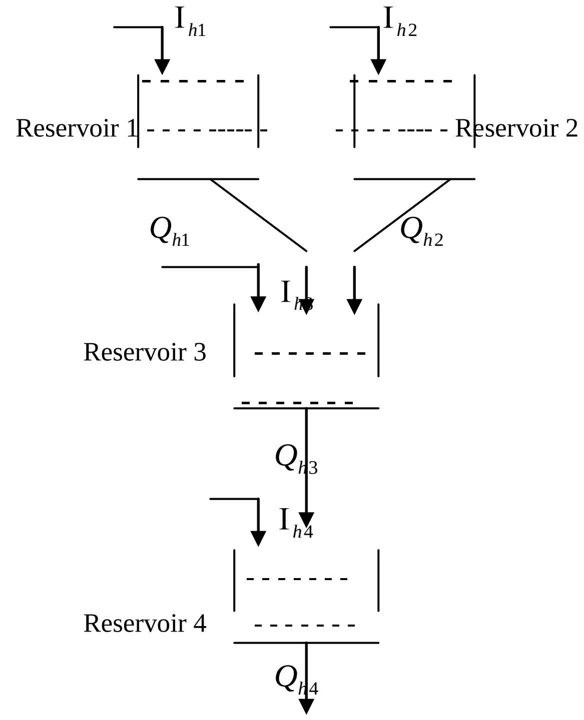
8. APPENDIX



Where:

I_{hj} : natural inflow to j th reservoir

Q_{hj} : discharge of j th plant

Plant	1	2	3	4
R_u	0	0	2	1
t_d	2	3	4	0

R_u : no of upstream plants

Figure 1: Hydraulic system network

t_d : time delay to immediate downstream plant

Table 8: Load demand

Hour	P_D (MW)	Hour	P_D (MW)	Hour	P_D (MW)
1	750	9	1090	17	1050
2	780	10	1080	18	1120
3	700	11	1100	19	1070
4	650	12	1150	20	1050
5	670	13	1110	21	910
6	800	14	1030	22	860
7	950	15	1010	23	850
8	1010	16	1060	24	800

Table 9: Hydro power generation coefficients

Plant	C_1	C_2	C_3	C_4	C_5	C_6
1	-0.0042	-0.42	0.030	0.90	10.0	-50
2	-0.0040	-0.30	0.015	1.14	9.5	-70
3	-0.0016	-0.30	0.014	0.55	5.5	-40
4	-0.0030	-0.31	0.027	1.44	14.0	-90

Table 10: Reservoir inflows ($\times 10^4 m^3$)

Hour	Reservoir 1 2 3 4	Hour	Reservoir 1 2 3 4	Hour	Reservoir 1 2 3 4
1	10 8 8.1 2.8	9	10 8 1 0	17	9 7 2 0
2	9 8 8.2 2.4	10	11 9 1 0	18	8 6 2 0
3	8 9 4 1.6	11	12 9 1 0	19	7 7 1 0

4	7 9 2 0	12	10 8 2 0	20	6 8 1 0
5	6 8 3 0	13	11 8 4 0	21	7 9 2 0
6	7 7 4 0	14	12 9 3 0	22	8 9 2 0
7	8 6 3 0	15	11 9 3 0	23	9 8 1 0
8	9 7 2 0	16	10 8 2 0	24	10 8 0 0

Table 11: Reservoir storage capacity limits, plant discharge limits, reservoir end conditions ($\times 10^4 m^3$) and plant generation limits (MW)

Plant	$V^{\min}$	$V^{\max}$	V_{ini}	V_{end}	$Q^{\min}$	$Q^{\max}$	$P_h^{\min}$	$P_h^{\max}$
1	**80**	**150**	**100**	**120**	**5**	**15**	**0**	**500**
2	**60**	**120**	**80**	**70**	**6**	**15**	**0**	**500**
3	**100**	**240**	**170**	**170**	**10**	**30**	**0**	**500**
4	**70**	**160**	**120**	**140**	**6**	**20**	**0**	**500**

Table 12: Cost curve coefficients and operating limits of thermal generators

Unit	a_s	b_s	c_s	d_s	e_s	$P_s^{\min}$	$P_s^{\max}$
	\$/h	\$/MWh	\$/(MW)^{2}h	\$/h	rad/MW	MW	MW
1	100	2.45	0.0012	160	0.038	20	175
2	120	2.32	0.0010	180	0.037	40	300
3	150	2.10	0.0015	200	0.035	50	500

Transmission loss coefficients are given below:

B = 10^{-4} × [0.34 0.13 0.09 -0.01 -0.08 -0.01 -0.02
0.13 0.14 0.10 0.01 -0.05 -0.02 -0.01
0.09 0.10 0.31 0.00 -0.11 -0.07 -0.05
-0.01 0.01 0.00 0.24 -0.08 -0.04 -0.07 per MW
-0.08 -0.05 -0.11 -0.08 1.92 0.27 -0.02
-0.01 -0.02 -0.07 -0.04 0.27 0.32 0.00
-0.02 -0.01 -0.05 -0.07 -0.02 0.00 1.35]

B0 = 10^{-6} × [-0.7500 -0.0600 0.7000 -0.0300 0.2700 -0.7700 -0.0100]

B00 = 0.55 MW